MAG REPORT NO. 81-1

#1
Feb 1981

# EVALUATION OF MULTIPLE REGRESSION MODELS FOR PREDICTION OF WESTERN SPRUCE BUDWORM DEFOLIATION ON DOUGLAS-FIR

U.S.D.A. - FOREST SERVICE
FOREST PEST MANAGEMENT
METHODS APPLICATION GROUP
2810 CHILES ROAD
DAVIS, CA. 95616

TABLE OF CONTENTS

Report 81-1

3400
February 1981

# EVALUATION OF MULTIPLE REGRESSION MODELS FOR PREDICTION OF WESTERN SPRUCE BUDWORM DEFOLIATION ON DOUGLAS-FIR[1]

Allan T. Bullard and John Wong[2]

## ABSTRACT

*Physical attribute data of sampling locations were combined with egg mass densities in an attempt to improve forcasts of western spruce budworm defoliation in Douglas-fir using multiple regression analysis. Comparisons were made to determine the suitability of these equations for predicting defoliation with and without using physical attribute data. Results indicate that the inclusion of these variables does not improve defoliation prediction appreciably.*

## INTRODUCTION

Egg mass density has been used for many years to monitor population trends, evaluate long-term effects of control projects, and to forecast defoliation caused by the western spruce budworm, Choristoneura occidentalis Freeman. Inconsistency of results when applying locally applicable sampling schemes to predict western spruce budworm defoliation on Douglas-fir throughout the west led to the formation of a westwide Western Spruce Budworm Egg Mass-Defoliation Working Group in 1976 (Grimble and Young 1977).

Analysis of a three-year data base developed by that Group using standard linear regression techniques explained less than 50 percent of the variation, i.e., $R^2 < 0.50$. This indicated that factors other than egg mass density might be exerting a substantial influence on defoliation and the ability to predict it (Bullard and Young 1980). Based on work with the Douglas-fir

---

1 This study was partially funded by the Canada/US Spruce Budworms Program-West.

2 Authors are, respectively, Survey Entomologist and Mathematical Statistician, USDA Forest Service, Forest Pest Management, Methods Application Group, Davis, CA 95616. Mr. Bullard's present position is FPM-Field Office Representative, USDA Forest Service, Morgantown Field Office, Northeastern Area, Morgantown, WV 26505. The assistance of David Sharpnack and Kim Smith of the Biometrics Staff of the Pacific Southwest Forest and Range Experiment Station, Berkeley, CA 94701 is gratefully acknowledged.

tussock moth, Orgyia pseudotsuga McDunnough, by Stoszek (1977) and Heller and Miller (1977), who investigated the value of physical variables as predictors of risk of defoliation, it was felt that integration of those physical variables might improve the predictive model for the western spruce budworm. A proposal to do this work was submitted and subsequently funded by the Canada/U.S. Spruce Budworm Program-West (CANUSA-West).

## OBJECTIVE

The objective of the CANUSA-funded project was to refine the models for predicting western spruce budworm defoliation on Douglas-fir westwide through incorporation of physical attribute data associated with each cluster.

## METHODS

### Field and Laboratory Procedures

No changes were made in the methods previously described by Bullard and Young (1980) for collection of egg mass and defoliation estimation data. Form 1 was designed and distributed to the field for collection of physical data describing those clusters already contained in the data base and any new clusters being added. Variables included were slope, aspect, elevation, physiographic location, stand structure, species composition, and basal area.

Slope, elevation and basal areas were recorded as continous variables with aspect, physiographic location, stand structure and species composition recorded according to the following coded values:

| Aspect | Code |
|---|---|
| North | 1 |
| Northeast | 2 |
| East | 3 |
| Southeast | 4 |
| South | 5 |
| Southwest | 6 |
| West | 7 |
| Northwest | 8 |
| Flat | 9 |

| Physiographic Location | Code |
|---|---|
| Ridge top | 1 |
| Upper slope | 2 |
| Mid slope | 3 |
| Lower slope | 4 |
| Bench or flat | 5 |
| Stream bottom | 6 |

Form 1
WESTERN SPRUCE BUDWORM
EGG MASS-DEFOLIATION SURVEY
Cluster Identification/Data Form

| Survey Code | Form | Year | Region | Host | Forest | Unit | Cluster |
|---|---|---|---|---|---|---|---|
| (1-3) | (4) | (5-6) | (7-8) | (9-10) | (11-12) | (13-14) | (15-17) |
| 222 | 1 | | | | | | |

(21 - 28)

1. Range ___, Township ___, Section __ ____ (29 - 33)

2. Slope. Degree of slope to nearest 5° _________ ____ (34 - 38)

3. Aspect. Direction to nearest quadrant_________ ____ (39 - 43)

4. Elevation. In feet to nearest 100 feet ________ ____ (44 - 48)

5. Physiographic site _________ ____ (49 - 53)

6. Species composition _________ ____ (54 - 58)

7. Stand structure _________ ____ (59 - 63)

8. Basal area _________ ____

9. Comments _________

Date_________ Prepared by_________

1/81

| Stand Structure | Code |
|---|---|
| Multistory, open canopy | 1 |
| Multistory, closed canopy | 2 |
| Single story, open canopy | 3 |
| Single story, closed canopy | 4 |

| Species Composition | Code |
|---|---|
| Douglas-fir | 1 |
| Grand fir | 2 |
| White fir | 3 |
| Douglas-fir/Grand fir | 4 |
| Douglas-fir/white fir | 5 |
| Mixed conifer | 6 |

## Analysis

The objective of our analysis was to develop defoliation prediction equations using the stand variables described in addition to cluster egg-mass density as independent variables. Equations relating adjusted defoliation[1] as the dependent variable and cluster egg-mass density as the independent variable were reported (Bullard and Young 1980). In this study, we focused our interests on developing appropriate prediction equations by including all stand variables in one case, and more importantly from a statistical point of view, the case when only significant variables are included. These equations provide a means of determining improvement, if any, to the previously documented equations in the prediction of defoliation.

Regional Entomological Unit data were grouped according to the age of the infestation (table 1). Infestation age was determined as follows:

$$IA = (X-Y)+1$$

where $IA$ = infestation age
$X$ = year of survey
$Y$ = year defoliation was first recorded on aerial sketch maps of the entomological unit.

Data for this analysis were provided only by USDA Forest Service Regions 1 and 4.

1 The adjusted defoliation is the result of subtracting 12.5 from the observed defoliation.

Table 1. Entomological Unit data grouped by infestation age.

| Region | Entomological Unit | Age of Infestation (in years) 1 | 2 | 3 | 4 | >5 |
|---|---|---|---|---|---|---|
| 1 | 3-1 | | | | | 78-79[1] |
| | 11-1 | | | 76-77 | 77-78 | 78-79 |
| | 11-2 | | | 76-77 | 77-78 | 78-79 |
| | 11-3 | | | 76-77 | 77-78 | 78-79 |
| | 12-1 | | | | | 78-79 |
| | 12-2 | | | | | 78-79 |
| | 12-4 | | | | | 78-79 |
| 4 | 3-3 | | | 76-77 | 77-78 | 78-79 |
| | 12-50 | | | | | 77-78 |
| | 13-4 | 76-77 | 77-78 | 78-79 | | |
| | 15-1 | | 76-77 | 77-78 | 78-79 | |
| | 15-2 | | 76-77 | 77-78 | 78-79 | |

1 Years egg mass-defoliation were recorded respectively.

The general form of the model equation is as follows:

$$Y = a_0+a_1x_1+a_2x_2+\ldots\ldots\ +a_nx_n \qquad (1)$$

where $x_i$'s are the independent variables, $a_i$'s are the coefficients, $a_0$ is the intercept, and Y is the dependent variable. The objective was to determine the coefficients and the intercept for the model.

Site and stand class were separately entered into the above equation, each as a unique set of dummy variables. For each of the two dummy variables set, a value of one was assigned if a particular site index or stand class was present on a cluster and zero otherwise. Since the variable for site could take on an integer value from one to six, five dummy variables were introduced into the equation corresponding to site index one to five. The contribution to the regressions from site index six was obtained by assigning a zero to each of the five dummy variables. This then appears as a component and is included as part of the intercept. Similarly, for stand class, which could take on an integer value from one to four, three dummy variables were used.

Linear transformations were applied to the stand variables aspect and slope. This was accomplished by extending the relationship for the effect of slope and aspect on tree growth (Stage 1976) to defoliation. The following expressions are used to account for the contribution to the regression from these variables:

SlopexSIN((Aspect-1)x0.7854), and
SlopexCOS((Aspect-1)x0.7854).

where: the value 0.7854 is the angle of 45 degrees expressed in radians.

Our analysis consisted of two steps. First we selected the best variable set for each of the following cases: one variable, two variables, three variables, and up to six variables. The selection criterion was based on the concept of total squared error, or the $C_p$ statistic (Daniel and Woods 1971). This statistic measures the sum of the squared biases plus the squared random errors in the dependent variable at all data points, i.e., clusters. The best variable set, in each of the above cases is therefore associated with the smallest $C_p$. With this information, a multiple regression program[1] was then used to obtain the required coefficients for the appropriate model.

## Evaluation of Prediction Accuracy

Since the equations developed were based on cluster-level summaries and the overall objective was prediction of defoliation on Entomological Units represented by clusters, each unit was evaluated separately. For each unit, the individual cluster data were entered into the equation being evaluated and used to calculate adjusted defoliation estimates. Each of these estimates was then converted to the proper defoliation category (table 2) and an average defoliation prediction category determined for the unit. The actual adjusted defoliation recorded for each cluster on the unit was also converted to the proper defoliation category and an average actual defoliation category determined. The predicted unit defoliation category was compared to the actual unit defoliation category to determine the accuracy of the prediction.

---

1 Program P1R from the BMDP analysis package at UCLA was used for this analysis.

Table 2. Adjusted defoliation and defoliation categories.

| Adjusted Defoliation (percent) | Defoliation Category |
|---|---|
| <12.5 | 1 |
| 12.5-37.5 | 2 |
| 37.5-62.5 | 3 |
| >62.5 | 4 |

## RESULTS

From the regression program, values for multiple R-square ($R^2$), standard error of estimate ($Sy \cdot x$), mean ($\bar{Y}$), sample size (N), and the F ratio, are provided for each region by age of infestation. Table 3 summarizes the results using all data available for the independent variables and the adjusted defoliation for each cluster repeated.

Table 3. Results from regression analysis using all variables.

| Region | Age of Infestation | $R^2$ | $Sy \cdot x$ | $\bar{Y}$ | N | F |
|---|---|---|---|---|---|---|
| 1 | 3 | 0.600 | 16.117 | 54.907 | 53 | 4.514** |
| | 4 | 0.276 | 19.206 | 49.648 | 51 | 1.089*** |
| | 5 | 0.188 | 13.229 | 34.752 | 103 | 1.589* |
| 4 | 1 | 0.924 | 5.866 | 20.811 | 18 | 3.741* |
| | 2 | 0.642 | 8.763 | 23.967 | 66 | 7.199** |
| | 3 | 0.446 | 14.076 | 30.785 | 99 | 5.265** |
| | 4 | 0.611 | 15.557 | 41.092 | 78 | 7.761** |
| | 5 | 0.525 | 16.255 | 28.958 | 56 | 3.584** |

* Significant level at 10%.
** Significant level at 5%.
*** Not significant.

Regression analysis on R-1 data included information for those entomological units for which there were less than ten clusters reported. These data were excluded from our previous analysis as documented in MAG Report 80-10. The reason for including these additonal records was an attempt to obtain better estimates of the regression parameters.

Using the same procedures the data were reanalyzed using only those independent variables which were considered to be statistically significant (at $\alpha = 0.05$) based on the sequential F-test (Draper and Smith 1966). Regression statistics are shown in table 4.

Table 4. Results from regression analysis using only significant variables.

| Region | Age of Infestation | Selected Variables | $R^2$ | $S_{y \cdot x}$ | $\bar{Y}$ | N |
|---|---|---|---|---|---|---|
| 1 | 3 | egg mass | 0.492 | 15.896 | 54.909 | 53 |
| | 4 | egg mass | 0.128 | 18.316 | 49.648 | 51 |
| | 5 | intercept only | - | - | 34.752 | 103 |
| 4 | 1 | egg mass, | 0.725 | 5.572 | 20.811 | 18 |
| | 2 | egg mass, elevation, | 0.564 | 8.789 | 23.967 | 66 |
| | 3 | egg mass, stand class, | 0.397 | 13.959 | 30.785 | 99 |
| | 4 | egg mass, site, | 0.573 | 15.484 | 41.092 | 78 |
| | 5 | egg mass, slope, aspect | 0.279 | 18.014 | 28.958 | 56 |

Prediction equations. Two equations will be displayed for each Region and age class, the first including all independent variables, and the second equation using only significant variables. The definitions for the variable names appearing on these equations are:

> DEF = predicted defoliation, EM = egg-mass density, EL = elevation, BA = basal area, ASP = aspect, SL = slope, S1 = site index 1, S2 = site index 2, S3 = site index 3, S4 = site index 4, S5 = site index 5, STD1 = stand class 1, STD2 = stand class 2 and STD3 = stand class 3.

Region 1, three-year infestation:

$$\begin{aligned} DEF = {} & 8.16382+0.49067xEM+0.00399xEL \\ & + 0.02978xBA-0.07341xSLxSIN((ASP-1)x0.7854) \\ & + 0.06457xSLxCOS((ASP-1)x0.7854) \\ & + 28.25854xS1+3.32336xS2-12.67243xS3 \\ & + 1.68254xS4+1.46410xS5+4.31293xSTD1 \\ & + 4.01496xSTD2-0.62521xSTD3 \end{aligned} \qquad (2)$$

$$DEF = 34.70030+0.49778xEM \qquad (3)$$

Region 1, four-year infestation:

$$\begin{aligned} DEF = {} & -22.61531+0.42081xEM+0.00576xEL \\ & -0.00739xBA-0.04774xSLxSIN((ASP-1)x0.7854) \\ & -0.05173xSLxCOS((ASP-1)x0.7854) \\ & +7.03949xS1+25.04564xS2+24.54814xS3 \\ & +26.02119xS4+19.19623xS5+7.54262xSTD1 \\ & +6.26782xSTD2+8.90901xSTD3 \end{aligned} \qquad (4)$$

$$DEF = 40.24490+0.35781xEM \qquad (5)$$

Region 1, five-year infestation:

$$\begin{aligned} DEF = {} & 32.85489+0.09495xEM-0.00269xEL \\ & +0.14002xBA-0.01657xSLxSIN((ASP-1)x0.7854) \\ & -0.00435xSLxCOS((ASP-1)x0.7854) \\ & +0.27129xS1-4.29985xS2-11.60049xS3 \\ & -7.40518xS4-1.06105xS5+7.77288xSTD1 \\ & -0.18362xSTD2+9.74708xSTD3 \end{aligned} \qquad (6)$$

$$DEF = 32.01122$$

Region 4, one-year infestation:

$$\begin{aligned} DEF = {} & -2.79855+0.17265xEM+0.00712xEL \\ & +0.13830xBA-0.35560xSLxSIN((ASP-1)x0.7854) \\ & -0.75943xSLxCOS((ASP-1)x0.7854) \\ & -4.95770xS1-20.27609xS2-17.17468xS3 \\ & -12.92037xS4-9.41150xS5-30.99141xSTD1 \\ & -43.91933xSTD2-2.71478xSTD3 \end{aligned} \qquad (8)$$

$$DEF = 14.93243+4.68.208xEM \qquad (9)$$

Region 4, two-year infestation:

```
DEF = 48.30441+0.32772xEM-0.00462xEL
      +0.00919xBA-0.15962xSLxSIN((ASP-1)x0.7854)
      -0.19934xSLxCOS((ASP-1)x0.7854)
      +5.44137xS1+3.87339xS2+0.69888xS3
      +5.61072xS4+2.8591xS5-2.42510xSTD1
      - 5.33479xSTD2+3.96908xSTD3                    (10)

DEF = 63.11813+0.39661xEM-0.00657xEL                 (11)
```

Region 4, three-year infestation:

```
DEF = 34.11829+0.40185xEM+0.00058xEL
      +0.02247xBA-0.06987xSLxSIN((ASP-1)x0.7854)
      -0.03032xSLxCOS((ASP-1)x0.7854)
      -8.51244xS1-9.40816xS2-1.99559xS3              (12)
      -0.61939xS4-9.32359xS5-14.12642xSTD1
      -12.23585xSTD2+5.50520xSTD3

DEF = 28.70110+0.44072xEM-7.2916xSTD1
      -6.8351xSTD2+10.03228xSTD3                     (13)
```

Region 4, four-year infestation:

```
DEF = 77.11913+0.62270xEM-0.00835xEL
      -0.01280xBA-0.09509xSLxSIN((ASP-1)x0.7854)
      -0.08264xSLxCOS((ASP-1)x0.7854)
      +21.97305xS1+3.85536xS2+13.76373xS3
      +13.81682xS4+2.30643xS5-3.20923xSTD1
      -3.34612xSTD2+10.41419xSTD3                    (14)

DEF = 28.90201+0.76132xEM+22.63379xS1
      +3.05382xS2+12.41811xS3+13.89129xS4
      +2.43637xS5                                    (15)
```

Region 4, five-year infestation:

```
DEF = 53.26370+0.21431xEM+0.00814xBA
      -0.19791xBA-0.25947xSLxSIN((ASP-1)x0.7854)
      -0.20653xSLxCOS((ASP-1)*0.7854)-69.15392xS1
      -65.44893xS2-65.48030xS3-70.678.04xS4
      -67.61917xS5+3.81566xSTD1-50.09532xSTD2
      -22.48822xSTD3                                 (16)

DEF = 20.06143+0.36009xEM
      -0.22979xSLxSIN((ASP-1)x0.7854)
      -0.19550xSLxCOS((ASP-1)x0.7854)                (17)
```

The range of values for the independent variables, the dependent variables, the means, and the standard deviation are provided in Appendix A-H. An important point to be made here is that in using these equations for prediction, the input values for the independent variables must fall within the range of the input data from which these equations were established.

The results of the evaluation of various equations are shown in Tables 5 and 6.

Table 5. Predicted average defoliation category by equation vs. actual average defoliation category (R-1).

| E.U. | Date | Age of Infestations (in years) | N | Avg. actual Defoliation category | Predicted Defoliation category (Full model)[1] | Predicted Defoliation category (Reduced model)[2] |
|---|---|---|---|---|---|---|
| 3-1 | 78-79 | 5 | 9 | 2 | 2 | 2 |
| 11-1 | 76-77 | 3 | 10 | 3 | 3 | 3 |
| | 77-78 | 4 | 11 | 3 | 3 | 3 |
| | 78-79 | 5 | 12 | 2 | 2 | 2 |
| 11-2 | 76-77 | 3 | 17 | 3 | 3 | 3 |
| | 77-78 | 4 | 15 | 3 | 3 | 3 |
| | 78-79 | 5 | 18 | 2 | 2 | 2 |
| 11-3 | 76-77 | 3 | 8 | 3 | 3 | 3 |
| | 77-78 | 4 | 7 | 2 | 3 | 3 |
| | 78-79 | 5 | 17 | 2 | 2 | 2 |
| 12-1 | 78-79 | 5 | 21 | 2 | 2 | 2 |
| 12-2 | 78-79 | 5 | 12 | 2 | 2 | 2 |
| 12-4 | 78-79 | 5 | 9 | 2 | 2 | 2 |

1 Model using all variables.

2 Model based on significant variables.

Table 6. Predicted average defoliation category by equation vs. actual average defoliation category (R-4).

| E.U. | Date | Age of Infestations (in years) | N | Avg. actual Defoliation category | Predicted Defoliation category (Full model) | Predicted Defoliation category (Reduced model) |
|---|---|---|---|---|---|---|
| 3-3 | 76-77 | 3 | 36 | 2 | 2 | 2 |
| | 77-78 | 4 | 32 | 2 | 2 | 2 |
| | 78-79 | 5 | 27 | 2 | 2 | 2 |
| 12-50 | 77-78 | 5 | 14 | 2 | 2 | 2 |
| | 78-79 | 5 | 15 | 2 | 2 | 2 |
| 13-4 | 76-77 | 1 | 18 | 2 | 2 | 2 |
| | 77-78 | 2 | 18 | 2 | 2 | 2 |
| | 78-79 | 3 | 16 | 2 | 2 | 2 |
| 15-1 | 76-77 | 2 | 25 | 2 | 2 | 2 |
| | 77-78 | 3 | 25 | 2 | 2 | 2 |
| | 78-79 | 4 | 25 | 3 | 2 | 2 |
| 15-2 | 76-77 | 2 | 23 | 2 | 2 | 2 |
| | 77-78 | 3 | 22 | 2 | 2 | 2 |
| | 78-79 | 4 | 21 | 2 | 2 | 2 |

As can be seen by reviewing Tables 5 and 6, both the full and the reduced models performed identically in predicting proper defoliation categories. In Region 1, 12 of 13 Entomological Units were correctly predicted by both equations, and in Region 4, both equations predicted 13 of 14 correctly. Both equations in both Regions incorrectly predicted defoliation in the same Entomological Unit.

One of the purposes of this CANUSA-funded study was to determine if the addition of site characteristic variables would improve prediction of WSBW defoliation over a simple linear approach. Tables 7 and 8 present a comparison by Region of the correct predictions for identical Entomological Units using the linear equations in the form Y=a+bx as reported by Bullard and Young (1980) and the equations presented in this report.

Table 7. Comparison of prediction using the simple linear model full model and reduced model (R-1). (C=correct, I=incorrect)

| E.U. | Date | Age of Infestations (in years) | Simple linear Model | Full Model | Reduced Model |
|---|---|---|---|---|---|
| 3-1 | 78-79 | 5 | C | C | C |
| 11-1 | 76-77 | 3 | C | C | C |
| | 77-78 | 4 | C | C | C |
| | 78-79 | 5 | C | C | C |
| 11-2 | 76-77 | 3 | C | C | C |
| | 77-78 | 4 | C | C | C |
| | 78-79 | 5 | C | C | C |
| 11-3 | 76-77 | 3 | C | C | C |
| | 77-78 | 4 | C | C | C |
| | 78-79 | 5 | I | I | I |
| 12-1 | 78-79 | 5 | C | C | C |
| 12-2 | 78-79 | 5 | C | C | C |
| 12-4 | 78-79 | 5 | C | C | C |

Table 8. Comparison of prediction using the simple linear model, full model, and reduced model (R-4). (C=correct, I=incorrect)

| E.U. | Date | Age of Infestations (in years) | Simple linear Model | Full Multiple Model | Reduced Model |
|---|---|---|---|---|---|
| 3-3 | 76-77 | 3 | C | C | C |
| | 77-78 | 4 | C | C | C |
| | 78-79 | 5 | C | C | C |
| 12-50 | 77-78 | 5 | C | C | C |
| | 78-79 | 5 | C | C | C |
| 13-4 | 76-77 | 1 | C | C | C |
| | 77-78 | 2 | C | C | C |
| | 78-79 | 3 | C | C | C |
| 15-1 | 76-77 | 2 | C | C | C |
| | 77-78 | 3 | C | C | C |
| | 78-79 | 4 | I | I | I |
| 15-2 | 76-77 | 2 | C | C | C |
| | 77-78 | 3 | C | C | C |
| | 78-79 | 4 | C | C | C |

Examination of Tables 7 and 8 shows that in terms of correct prediction, all models in both Regions performed identically.

Tables 9 and 10 compare the multiple R square ($R^2$) values of the various equations by Region and their standard error of estimates ($S_{y \cdot x}$).

Table 9. Comparison of $R^2$ and Sy·x values of the simple linear models, full models, and reduced models by infestation age (R-1).

| Age of Infestation | Simple Linear Model | | Full Model | | Reduced Model | |
|---|---|---|---|---|---|---|
| | $R^2$ | Sy.x | $R^2$ | Sy.x | $R^2$ | Sy.x |
| 3 | 0.538 | 14.85 | 0.600 | 16.117 | 0.492 | 15.896 |
| 4 | 0.149 | 17.74 | 0.276 | 19.206 | 0.128 | 18.316 |
| 5 | 0.070 | 13.28 | 0.188 | 13.229 | - | - |

Table 10. Comparison of $R^2$ and Sy·x values of the simple linear models, full models, and reduced models by infestation age (R-4).

| Age of Infestation | Simple Linear Model | | Full Model | | Reduced Model | |
|---|---|---|---|---|---|---|
| | $R^2$ | Sy.x | $R^2$ | Sy.x | $R^2$ | Sy.x |
| 1 | 0.729 | 5.44 | 0.924 | 5.866 | 0.725 | 5.572 |
| 2 | 0.521 | 8.94 | 0.642 | 8.763 | 0.564 | 8.789 |
| 3 | 0.242 | 15.08 | 0.446 | 14.076 | 0.397 | 13.959 |
| 4 | 0.522 | 15.85 | 0.611 | 15.557 | 0.573 | 15.484 |
| 5 | 0.151 | 18.38 | 0.525 | 16.225 | 0.279 | 18.014 |

## DISCUSSION AND CONCLUSION

In all cases, the $R^2$ value using the full model is higher than that of either the simple linear model or the reduced model. This indicates that the full model explains more of the variability that exists in predicting defoliation than either of the other models. This is reasonable, as the full model utilizes characteristics that have been shown to exert an influence on defoliation by other workers studying other insects (Stosyck 1977, and Heller and Miller 1977).

Use of the full multiple regression models presented in this report will provide an increase in $R^2$, or explain more variability in prediction of WSBW defoliation, than either a simple linear approach using cluster egg mass density or use of a reduced model including only significant variables. Due to the complexity of the full model, the lack of improvement in correctly predicting defoliation on an Entomological Unit basis by use of the full model over either the simple linear models presented by Bullard and Young (1980) or the reduced model, the inconsistency of variables shown to be significant in predicting defoliation by the reduced model and the increases in both dollars and time required to collect the cluster attribute data to use the full multiple regression model, it is recommended that the simple linear equations presented earlier (Bullard and Young 1980) be used to predict WSBW defoliation.

# LITERATURE CITED

Bullard, A.T. and R.W. Young. 1980. Prediction of Western spruce budworm defoliation on Douglas-fir. Forest Insect and Disease Management, Methods Application Group, Davis, California. 52 pp.

Daniel, C. and F.S. Wood. 1971. Fitting equations to data. John Wiley & Sons, Inc. 342 pp.

Draper, N.R. and H. Smith. 1966. Applied regression analysis. John Wiley & Sons, Inc. 407 pp.

Grimble, D.G. and R.W. Young. 1977. Western spruce budworm egg mass-defoliation surveys. A working group progress report. USDA Forest Service MAG Rpt. No. 77-3. Forest Insect and Disease Management, Methods Application Group, Davis, California. 21 pp.

Heller, R.C. and W.A. Miller. 1977. Color infrared photos define site conditions favorable for Douglas-fir tussock moth outbreaks. IN Proceedings, Sixth Biennial Workshop on Aerial Color Photography in the Plant Sciences and Related Fields, August 9-11, 1977. Colorado State University, Ft. Collins, Colorado. pp 43-52.

Stage, A.R. 1976. An expression for the effect of aspect, slope, and habitat type on tree growth. Forest Science 22(4): 457-459.

Stoszek, K.J. 1977. Factors influencing tree and stand susceptibility to Douglas-fir tussock moth attack. Bull. Entomol. Soc. Amer. 23(3): 171-72.

# APPENDIX A

Mean, standard deviation and range of values for the variables used in equations 2 and 3.

| Variables | R-1 three-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 40.59 | 31.13 | 0.00 | 111.70 |
| adjusted defoliation | 54.91 | 22.09 | 12.50 | 87.50 |
| slope | 37.54 | 19.60 | 0.00 | 80.00 |
| aspect | 4.77 | 2.21 | 1.00 | 9.00 |
| elevation | 5526.37 | 446.97 | 4200.00 | 6800.00 |
| site | 3.90 | 0.86 | 1.00 | 6.00 |
| stand | 2.07 | 1.11 | 1.00 | 4.00 |
| basal area | 98.07 | 48.54 | 2.00 | 216.00 |

## APPENDIX B

Mean, standard deviation and range of values for the variables used in equations 4 and 5.

| Variables | R-1 four-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 26.28 | 19.48 | 0.80 | 85.90 |
| adjusted defoliation | 49.65 | 19.43 | 17.70 | 86.20 |
| slope | 36.47 | 19.98 | 0.00 | 80.00 |
| aspect | 4.92 | 2.32 | 1.00 | 9.00 |
| elevation | 5529.00 | 503.70 | 4200.00 | 6800.00 |
| site | 3.86 | 0.96 | 1.00 | 6.00 |
| stand | 2.06 | 1.12 | 1.00 | 4.00 |
| basal area | 98.63 | 49.23 | 2.00 | 216.00 |

APPENDIX C

Mean, standard deviation and range of values for the variables used in equations 6 and 7.

| Variables | R-1 five-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 41.44 | 36.12 | 2.10 | 28.07 |
| adjusted defoliation | 34.75 | 13.72 | 14.00 | 75.80 |
| slope | 33.20 | 19.21 | 0.00 | 80.00 |
| aspect | 4.56 | 2.39 | 1.00 | 9.00 |
| elevation | 5399.89 | 547.53 | 4100.00 | 6900.00 |
| site | 3.89 | 1.03 | 0.00 | 6.00 |
| stand | 2.06 | 1.10 | 1.00 | 4.00 |
| basal area | 95.28 | 43.77 | 2.00 | 216.00 |

# APPENDIX D

Mean, standard deviation and range of values for the variables used in equations 8 and 9.

| Variables | R-4 one-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 1.25 | 1.88 | 0.00 | 6.90 |
| adjusted defoliation | 20.81 | 10.32 | 12.79 | 57.00 |
| slope | 22.50 | 9.89 | 5.00 | 35.00 |
| aspect | 4.28 | 1.96 | 1.00 | 7.00 |
| elevation | 6516.65 | 737.45 | 4500.00 | 7700.00 |
| site | 2.89 | 1.28 | 1.00 | 6.00 |
| stand | 1.72 | 1.02 | 1.00 | 4.00 |
| basal area | 73.33 | 41.16 | 20.00 | 160.00 |

# APPENDIX E

Mean, standard deviation and range of values for the variables used in equations 10 and 11.

| Variables | R-4 two-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 12.79 | 22.95 | 0.00 | 90.30 |
| adjusted defoliation | 23.97 | 13.11 | 12.50 | 67.20 |
| slope | 15.00 | 9.32 | 5.00 | 35.00 |
| aspect | 4.92 | 1.92 | 1.00 | 9.00 |
| elevation | 6727.21 | 471.52 | 4500.00 | 7700.00 |
| site | 3.29 | 1.38 | 1.00 | 6.00 |
| stand | 1.60 | 0.80 | 1.00 | 4.00 |
| basal area | 76.21 | 36.11 | 20.00 | 180.00 |

# APPENDIX F

Mean, standard deviation and range of values for the variables used in equations 12 and 13.

| Variables | R-4 three-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 17.19 | 19.81 | 0.00 | 76.60 |
| adjusted defoliation | 30.78 | 17.61 | 12.50 | 83.79 |
| slope | 23.47 | 17.74 | 0.00 | 80.00 |
| aspect | 4.75 | 2.23 | 1.00 | 9.00 |
| elevation | 6634.26 | 417.49 | 5800.00 | 7700.00 |
| site | 3.44 | 1.24 | 1.00 | 6.00 |
| stand | 1.41 | 0.74 | 1.00 | 4.00 |
| basal area | 72.12 | 33.96 | 20.00 | 180.00 |

## APPENDIX G

Mean, standard deviation and range of values for the variables used in equations 14 and 15.

| Variables | R-4 four-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 17.81 | 20.66 | 0.00 | 79.00 |
| adjusted defoliation | 41.09 | 22.77 | 13.09 | 87.39 |
| slope | 23.01 | 18.71 | 0.00 | 80.00 |
| aspect | 4.72 | 2.23 | 1.00 | 9.00 |
| elevation | 6647.35 | 373.75 | 5800.00 | 7300.00 |
| site | 3.50 | 1.22 | 1.00 | 6.00 |
| stand | 1.38 | 0.69 | 1.00 | 4.00 |
| basal area | 74.10 | 34.20 | 20.00 | 180.00 |

# APPENDIX H

Mean, standard deviation and range of values for the variables used in equations 16 and 17.

| Variables | R-4 five-year infestation | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Min. | Max. |
| egg-mass | 22.12 | 25.52 | 0.00 | 100.00 |
| adjusted defoliation | 28.96 | 20.63 | 12.50 | 86.00 |
| slope | 29.64 | 18.11 | 0.00 | 80.00 |
| aspect | 4.75 | 2.39 | 1.00 | 9.00 |
| elevation | 5580.31 | 1074.54 | 3600.00 | 7200.00 |
| site | 3.53 | 1.17 | 1.00 | 6.00 |
| stand | 1.16 | 0.56 | 1.00 | 4.00 |
| basal area | 69.11 | 37.19 | 20.00 | 180.00 |